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Applicability of Synthetic Aperture Radar (SAR) to Evaluate Leaf Area Index (LAI) and its Growth Rate of Rice in Farmers' Fields in Lao PDR

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Highlights

・This study applied SAR to estimate LAI and its growth rate in Lao PDR.
・Back scattering coefficient (BSC) of SAR was correlated with LAI and NDVI.
・Increase of BSC against day represented LAI growth.

ABSTRACT

Rice is the most important crop in Lao People's Democratic Republic (Lao PDR). Synthetic aperture radar (SAR) is proposed as a more suitable method to evaluate rice growth in this area because it is independent from cloud and solar illumination. This study analyzed the relationship between the back scattering coefficient (BSC) in SAR images and leaf area index (LAI) of rice. Here, we discuss the applicability of SAR to estimate LAI and its growth rate in farmers' fields in Lao PDR. 30 farmers' paddy fields were selected for surveying throughout the growth period in the wet season of 2013, and both LAI and normalized difference vegetation index (NDVI) were measured at 4 time periods before the heading period for each field. X-band SAR images from the COSMO-SkyMed system (SAR) were used in this study. BSC was significantly correlated with LAI and NDVI. BSC at 28 of 30 fields was positively correlated with days after transplanting (DAT), and 10 of these results were significant. The increased rate in BSC obtained at the fields where BSC and DAT had a significant correlation, were significantly correlated with that in LAI. This finding suggests that if SAR images demonstrate significant increases of BSC against DAT, the increased rate may also represent LAI growth rate, although uncontrollable water levels and weeds occasionally interrupt observation. This study demonstrates the capacity of SAR to evaluate rice production in developing countries.

Keywords:

Back scattering coefficient (BSC); farmers' fields; LAI; NDVI; rice; Synthetic aperture radar (SAR).

1. Introduction

Rice is undoubtedly the most important crop in the Lao People's Democratic Republic (Lao PDR), and approximately 70% of the total calories in the Lao diet come from rice (Maclean et al., 2002). While improving its productivity is strongly recommended, the information about rice growth characteristics in farmers' fields is limited (Bell and Seng, 2003; Fukai et al., 1999; Inamura et al., 2003). Hirooka et al. (2015) measured leaf area index (LAI) and its growth rate using a plant canopy analyzer and reported that rice production was closely associated with LAI growth rate. However, because application of a plant canopy analyzer is not suitable on a regional scale, the evaluation by satellite based remote sensing is recommended.

Most rice production in Lao PDR is conducted in the rainy season (Schiller, 2006), during which cloudy conditions often interrupt satellite observation in visible and near-infrared range. Accordingly, remote sensing based on synthetic aperture radar (SAR) is proposed as a more suitable method to evaluate rice growth in this area because the observation is independent from cloud and solar illumination (Chakraborty et al., 1997). The radar transmits a pulse and then measures the time delay and strength of the reflected echo, where the ratio of scattered and incident microwave energy is termed the back scattering coefficient (BSC) (Moran et al., 2002). SAR uses polarized radiation and, therefore, can exploit polarization signatures of the imaged scatters for obtaining more information about the scatter's structure (Bamler, 2000). Although previous studies investigated the applicability of SAR to estimate LAI (Inoue et al., 2014; Maki et al., 2015), the estimation accuracy has not attained practical level. The present study analyzed the relationship between SAR images and LAI of rice measured by Hirooka et al. (2015) and discusses the applicability of SAR to estimate LAI and its growth rate in farmers' fields in Lao PDR. The results showed although the accuracy was still the problems to estimate LAI, analyzing a sequence of BSC may provide a strategy to applicate SAR to evaluate rice production in developing countries.

2. Materials and Methods

2.1. Overview and test sites

This study used LAI data from farmers' fields in Vientiane province in 2013, Lao PDR (18°01' - 18°30'N, 102°24' - 103°02'E, 168 - 178 m asl.), observed by Hirooka et al. (2015). We analyzed SAR data in relation to LAI, together with the normalized difference vegetation index (NDVI) measured in the same fields.

30 farmers' paddy fields in this area were selected for surveying throughout the growth period (Hirooka et al., 2015). We selected the fields that had open space in the direction of satellite orbit (west and approximately 45º in the incident angle) and that were surrounded by relatively flat paddy fields (at least 1 ha in the area). The mean air temperature for the measuring period (from 22 July to 16 September) was 28.0 ºC. The longitude and latitude of the selected fields were recorded by Global Positioning System (GPSMAP 62SJ, Garmin International, Inc., Kansas City). The cultivation methods (direct seeding/transplanting, fertilizer, planting density and cultivar) of rice plants and field conditions (standing water and weeds) in the farmers' fields under investigation were checked by the authors' observation and interviews to farmers. The fields where the maximum depth of standing water exceeded more than 30 cm were classified as deep water fields, and the fields where weeds covered a maximum of 20% or more were classified as weedy fields in this study.

2.2. LAI measurement and analysis (Hirooka et al., 2015)

LAI was measured using a plant canopy analyzer (LAI-2200, LI-COR, Inc., Nebraska) with a single sensor mode in a sequence of two above and four below canopy with 5 replications at each field. To reduce the influence of the adjacent fields and the operator, a 90º view-cap was applied to the optical sensor. Measurements were conducted 4 times before the heading period (22 - 24 July, 10 - 12 August, 30 August - 1 September and 16 - 18 September). Since LAI linearly increased during the measurement, LAI growth rate was calculated using the following linear function (Eq (1); Hirooka et al., 2015).

$$\mathrm{LAI} = a * \mathrm{DAT} + b \quad (1)$$

DAT denotes days after transplanting, a represents LAI growth rate, and b represents approximate LAI at the transplanting date.

2.3. NDVI measurement

For measuring spectral reflectance of rice canopies, we used a spectroradiometer (MS-720, EKO Instruments Co., Ltd., Tokyo). MS-720 measures radiation from 350 nm to 1050 nm by 3.3 nm intervals. We measured the sky radiation with a FOV 180° attachment and the plant reflection with a FOV 45° attachment from 1 m above the rice canopies, with 3 replications at each field when we measured LAI. We calculated canopy reflectance by dividing plant radiation by sky radiation. We calculated the normalized difference vegetation index (NDVI) using canopy reflectance in RED (620-670 nm) and NIR (841–875 nm) (Eq (2)).

$$\mathrm{NDVI} = (\text{reflectance in NIR} - \text{reflectance in RED}) / (\text{reflectance in NIR} + \text{reflectance in RED}) \quad (2)$$

2.4. SAR images

X-band SAR images from the Constellation of Small Satellites for the Mediterranean Basin Observation COSMO-SkyMed system (ScanSAR Wide Region mode, HH polarization) were used in this study to acquire high temporal and spatial-resolution SAR data. COSMO-SkyMed can supply high temporal and spatial-resolution data by operating 4 satellites on the same orbit. All COSMO-SkyMed images used in this study were acquired during ascending orbit. The incidence angle for data acquisition was approximately 45°. Spatial resolution was adjusted to 30 m by multi-look processing and spatial filtering to reduce speckle noise. The 3 × 3 pixel Lee filter (Lee, 1980) was applied to the images used in this study. Back scattering coefficients (BSC) of SAR images is increased as rice plants grow in the paddy fields (Fig.1). Eight SAR images were obtained from the period between transplanting and heading: on 22 and 30 July, 7, 15, 23 and 31 August and 8 and 16 September. 4 SAR images on 22 July, 7 August, 31 August and 16 September were selected to analyze the relation with LAI and NDVI measured on 22 - 24 July, 10 - 12 Aug, 30 Aug - 1 Sep and 16 - 18 Sep, respectively.

3. Results and discussion

Back scattering coefficient (BSC) at the investigated fields in SAR images ranged from -18.3 to -1.57. LAI and NDVI ranged from 0.03 to 3.60 and from -0.24 to 0.81, respectively. BSC at 28 of 30 fields had a positive correlation with days after transplanting (DAT), corresponding with rice growth (Fig. 1). However, only 10 of these results were significant. Observations at the investigated fields indicated that non-significance was partly caused by deep water or weeds (see Fig. 3).

Fig. 2a shows that BSC was significantly correlated with LAI (LAI; $r = 0.584$, $p < 0.001$). Although the value was slightly lower than that previously reported (0.75 by Inoue et al., 2014), the difference might be derived from that between X-band and C-band. Previous studies also reported that BSC at rice fields showed saturation greater than 3 in LAI similar to the levels NDVI often suggested (see Fig2c; Capodici et al., 2013; Inoue et al., 2014). However, BSC in this study did not show such saturation due to moderate correlation with LAI. Deep water and weeds are generally the factors that disturbed the relationship between LAI and BSC because BSC is decreased by water (Martinez and Toan, 2007) and increased by weeds (Liew et al., 1998). In this study, however, the relationship did not improve even if weedy and DW fields were excluded from the analysis (Table 1). Fig. 2a and Table 1 shows that BSC and LAI had a closer correlation at the fields where BSC and DAT had a significant correlation. These results suggest that the possibility of estimating LAI is dependent on location and that the observed increase in BSC with DAT is a required condition. Field heterogeneity

(Miyaoka et al., 2013) or orientation of ridge in paddy fields (Yamaguchi et al., 2005) may cause such locational error. Although further study is necessary, selection of observation point on the basis of the relation between BSC and DAT in previous seasons probably improves the estimation accuracy for LAI with BSC.

Fig. 2b demonstrates that BSC was also correlated with NDVI ($r = 0.574$, $p < 0.001$). Although LAI and NDVI displayed a nonlinear relationship (Fig. 2c), no distinct difference was observed in the relationship between BSC and LAI and that between BSC and NDVI (Fig. 2a and Fig. 2b). Further studies are necessary to determine what structural factors in rice canopy affect BSC.

The increased rates of BSC against DAT obtained in the fields where BSC and DAT had a significant correlation were also significantly correlated with LAI growth rate (the regression line in Fig. 3). However, those fields in which BSC and DAT showed a non-significant correlation tended to yield lower values of BSC increase rate that expected from the regression line. This finding suggests that if a significant increase of BSC against DAT was obtained, the increased rate may represent LAI growth rate. Hirooka et al. (2015) reported that LAI growth rate was closely associated with soil C and N levels, which is a major indicator of soil fertility and consequent rice production in the study area. These facts suggest that soil fertility and rice productivity could be estimated from BSC even though LAI cannot be directly estimated from BSC.

Although LAI ordinarily shows curvilinear growth such as sigmoid, this study estimated the growth rate by a linear function (Eq. 1) according to Hirooka et al. (2015). The linear growth indicates that the observation was conducted after exponential growth and before saturated growth. Low LAI (see Fig. 3a) may help rice to keep linear growth of LAI before heading. To follow rice growth more precisely, more frequent measurements are necessary especially just after transplanting and around heading. Such frequent observation of LAI and BSC might improve the estimation of rice growth.

Rice production in Lao PDR is currently conducted on small and untidy paddy fields where many trees are left uncut (Kosaka et al., 2006; Miyagawa et al., 2013). Uncontrollable water levels (drought and deep water) and weeds often constrain rice production in this area (Inamura et al., 2003; Inthavong et al., 2011). These factors are unfavorable for evaluating rice growth by SAR images. The dependence on incidence angle and azimuth angle of the SAR sensor in the relationship between BSC and LAI should also be analyzed further in order to accurately estimate LAI (Gautier et al., 1998). Despite the remaining limitations, this study has demonstrated the capacity of SAR to evaluate rice production in developing countries. Combining an area map of planted rice as well as planting dates both of which are obtained from SAR images (Miyaoka et al., 2013; Maki et al., 2015) may help a more accurate evaluation of rice productivity.

Acknowledgements

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Figure captions

Fig.1 The map of Google earth (left) and synthetic aperture radar (SAR) images (center and right) for a part of the research area. Back scattering coefficient (BSC) is gray-scaled in the SAR images. The increase of BSC (gray in 22 July to white in 16 September) corresponded to the rice growth in paddy fields.

Fig. 2 Changes in the back scattering coefficient (BSC) with days after transplanting (DAT) at the two fields where BSC and DAT had a significant correlation. The slope of the regression line was defined as rate of BSC increase.

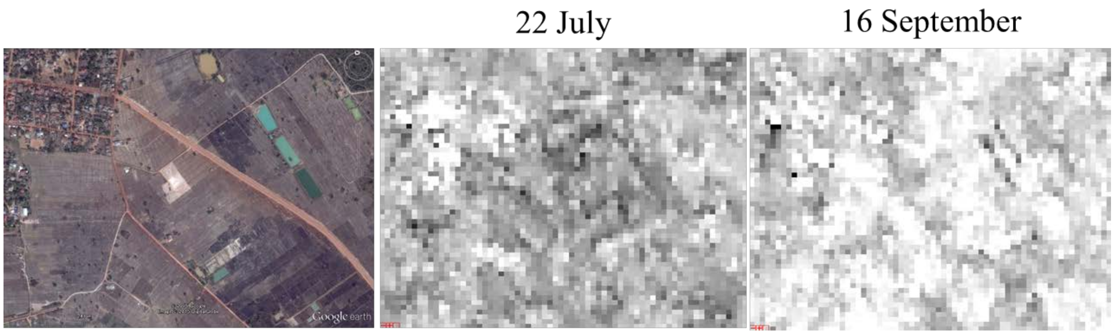
Fig. 3 Relationship between (a) back scattering coefficient (BSC) and leaf area index (LAI), (b) BSC and normalized difference vegetation index (NDVI), (c) LAI and NDVI. S: the field where BSC and DAT had a significant correlation. N: the field where BSC and DAT had a non-significant correlation. DW: the field that had more than 30 cm depth of standing water. Weed: the field covered by more than 20% weeds at the maximum.

Fig. 4 Relationship between leaf area index (LAI) growth rate (m^2 m^{-2} day^{-1}) and back scattering coefficient (BSC) increase rate (day^{-1}). The line was regressed by the field where BSC and DAT had a significant correlation (S). The symbols are the same in Fig. 3; The fields which were classified into DW or Weed at least one time in Fig. 3 were defined as DW or Weed fields, respectively.

Table 1 Correlation coefficients of back scattering coefficient (BSC) with leaf area index (LAI and normalized difference vegetation index (NDVI). Except DW: DW fields were excluded from the correlation; Except Weed: Weed fields were excluded from the correlation; Except N: the fields where BSC and DAT had a non-significant correlation were excluded from the correlation; see Fig. 3.

Table 1 Correlation coefficients of back scattering coefficient (BSC) with leaf area index (LAI) and normalized difference vegetation index (NDVI). Except DW: DW fields were excluded from the correlation; Except Weed: Weed fields were excluded from the correlation; Except N: the fields where BSC and DAT had a non-significant correlation were excluded from the correlation; see Fig. 3.

	LAI	NDVI
All	0.584	0.574
Except DW	0.551	0.509
Except Weeds	0.603	0.585
Except N	0.766	0.593



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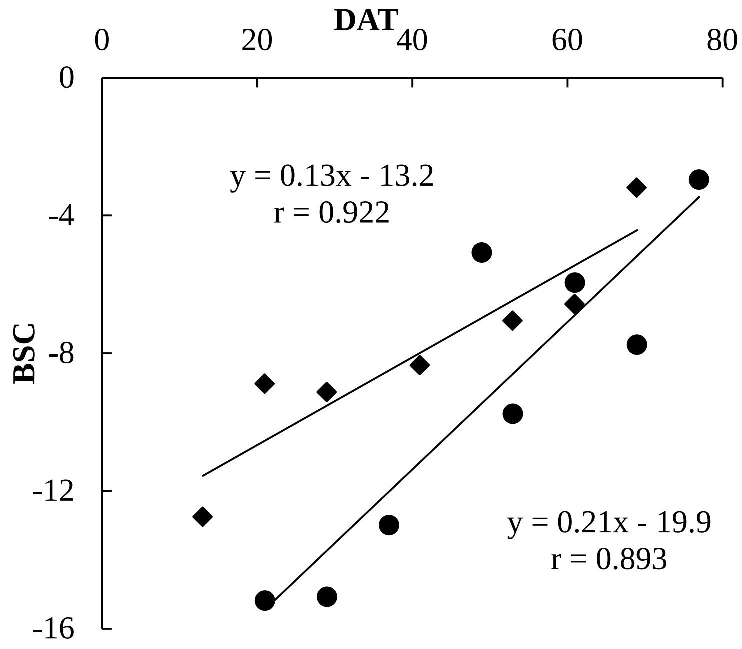

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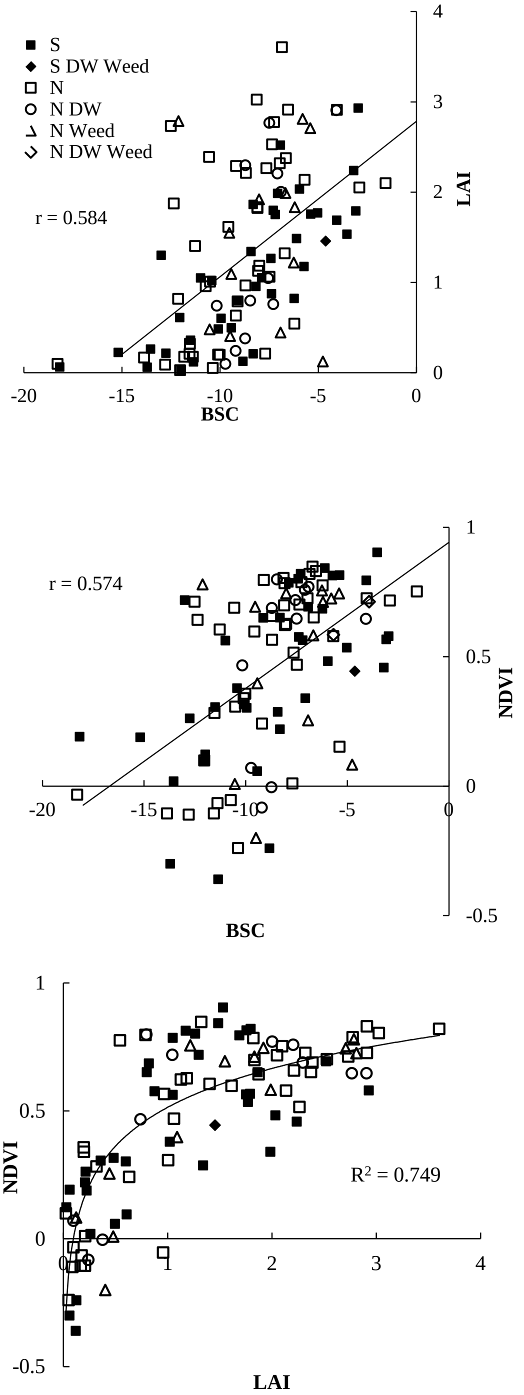
(a)
(b)
(c)



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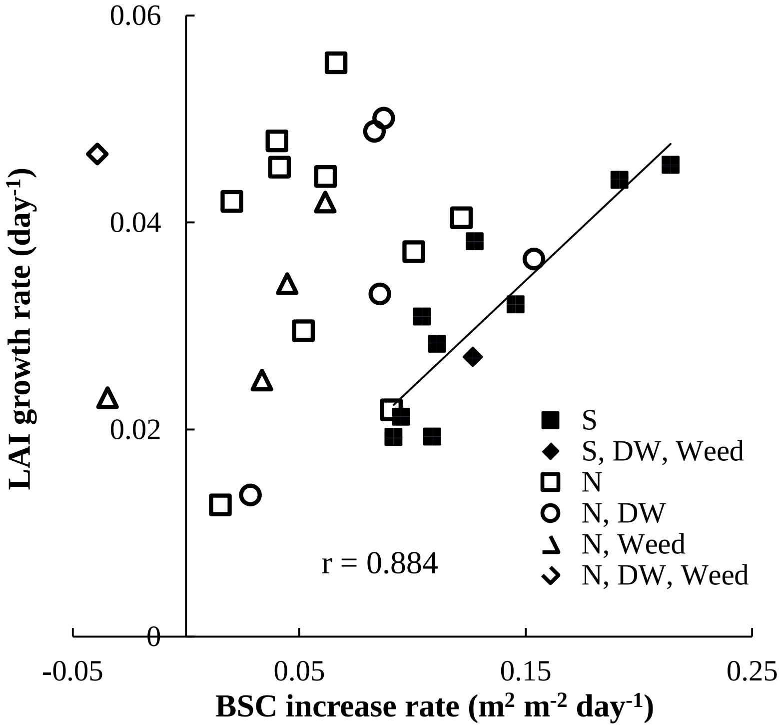

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